



# History of Thermal Barrier Coatings for Gas Turbine Engines

Emphasizing NASA's Role From 1942 to 1990

*Robert A. Miller*

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National Aeronautics and  
Space Administration

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# **History of Thermal Barrier Coatings for Gas Turbine Engines**

## **Emphasizing NASA's Role From 1942 to 1990**

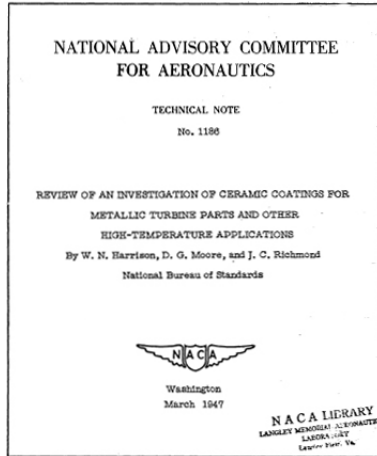
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### ***Outline***

- **NBS/NACA role in frit coatings**
- **Thermal spray coatings for rocket applications**
- **Stecura-Liebert zirconia-yttria TBCs**
- **Identification of optimum t'-ZrO<sub>2</sub> composition**
- **Failure mechanisms and life prediction**
- **Brief synopsis of post 1990 efforts**

## NACA's Earliest Turbine Blade-Oriented Ceramic Coatings Research was on NBS Frit Enamel Coatings 1942-1956

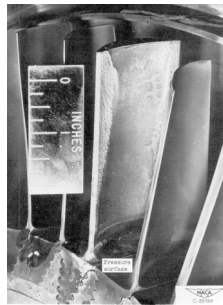
Probably the first aero ceramic coatings paper by Harrison & Moore, NBS – published as NACA TN in 1947



W.N. Harrison, D.G. Moore, and J.C. Richmond, "Review of an Investigation of Ceramic Coatings for Metallic Turbine Parts and Other High Temperature Applications," NACA TN-1186, National Advisory Committee for Aeronautics, 1947

## The NBS Frit Coating was tested on Turbine Blades in an Engine as Early as 1948

Figure from 1953 engine test (Bartoo & Clure).  
Coating on one blade lasted 100 hrs



Top Edge of an Air-Cooled Blade



E.R. Bartoo and J.L. Clure, "Experimental Investigation of Air-Cooled Turbine Blades in a **Turbojet** Engine, XIII. Performance Evaluation of Several Protective Coatings Applied to Turbine Blades of Nonstrategic Steels, NACA Research Memo E53E18, 1953

C.R. Morse, Comparison of National Bureau of Standards ceramic coatings L-7C and A-417 on turbine blades in a turbojet engine, NACA Research Memo E8120, 1948

F.G. Garrett and C.A. Gyorgak, "Adhesive and Protective Characteristics of Ceramic Coating A-417 and Its Effects on Engine Life of Forged Refractory-26 (AMS 5760) and Cast **Satellite** (AMS 5385) Turbine Blades," NACA RM-E52130, 1953

- **Also, frit coating development led by Air Force in the 40s, 50s and 60s**

A.V. Levy, Ceramic Coating for Insulation, Met. Prog., Vol. 75, 1959, pp. 86-89

**Durability questions followed all ceramic coatings for decades partly due to popular image of enameled kitchenware and possibly from negative Air Force results on engines in the 40s, 50s and 60s**



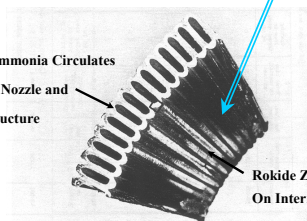
### **Flame Sprayed Coatings were Used for Rocket Applications**

The first and most visible was the use of Rokide™ Thermal Barrier Coatings on the XLR99 Rocket Engine Nozzles of the X-15, 1960



**X-15 Flight in Early 60s**

Liquid Ammonia Circulates  
Through Nozzle and  
Cools Structure



**Brazed Stainless Steel Tube Structure**

#### **Originally Coated with Rokide Z TBC**

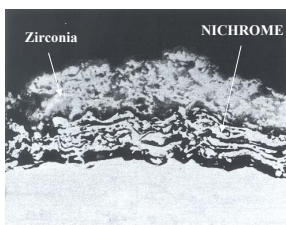
- Zirconia Top Coat/Nickel Chrome Bond Coat
- Prevents Oxidation of Tube Assembly
- Prevents Boiling of Liquid Ammonia



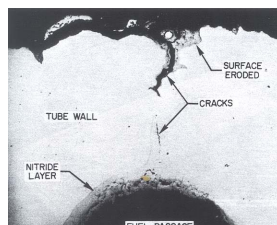
**Rokide Torch**

L.N. Hjelm and B.R. Bornhorst, "Development of Improved Ceramic Coatings to Increase the Life of XLR99 Thrust Chamber" Research Airplane-Committee Report on Conference on the Progress of the X-15 Project. NASA Tech Memo x-57072, 1961, 227-253.  
H. Davies, The Design and Development of the Thiokol XLR-99 Rocket Engine for the X-15 Aircraft, J Royal Aero Soc 67, 79-91, 196  
The XLR-99 development was managed out of Wright Patterson – Air Force Base, Robert L. Wiswell, X-15 Propulsion System, AIAA-1997-2682 AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, 33rd, Seattle, WA, July 6-9, 1997

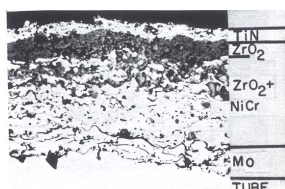
## Graded Rokide™ Thermal Barrier Coating Prevented Premature Failure of X-15 Combustion Chamber



Rokide Z Coating, As Processed



Spalled Region After Test



Graded Coating with Mo "Primer"

### Use of Graded Coating Significantly Improved Nozzle Life

- Grading Improved Coating Adhesion
- TiN Outer Layer Prevents Erosion (Chalking)

## TBCs Found Use in LH2/LOX Rocket Engine Development

- Development by NACA/NASA with Industrial Partners began in 1956



C. Leibert reported to me (personal communication ca. 1984) that TBCs were first used to extend life past one second!

Was a crucial step towards LH2/LOX rocket engine development  
NASA in Cleveland had a rocket-TBC group into the 1990s

H.G. Price Jr., R.L. Schacht, and R.J. Quentmeyer, "Reliability of Effective Thermal Conductivity of Three Metallic-Ceramic Composite Insulating Coatings on Cooled Hydrogen-Oxygen Rockets," NASA TN D-7392, 1973



### Materials-Oriented Thermal Spray Research in the 60s and Early 70s - Sal Grisaffe

- Sal conducted basic thermal spray research in 60s
- Alumina, Zirconia (Calcia and possibly Yttria stabilized) and Hafnia coatings for nuclear rocket applications in the early 70s
- He founded and headed the first coating's group in the 60s
- I joined the coatings group in 1978

Sal Grisaffe, 1961

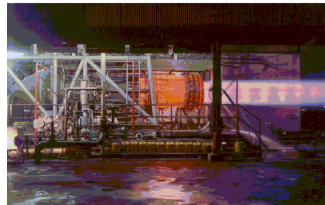


S.G. Grisaffe, Simplified Guide to Thermal-Spray Coatings, Mach. Des., Vol. 39, 1967, pp. 174-181  
A.N. Curren, S.G. Grisaffe, and K.C. Wycoff, "Hydrogen Plasma Tests of Some Insulating Coating Systems for the Nuclear Rocket Thrust Chamber," NASA TM X-2461, National Aeronautics and Space Administration, 1972

### Meanwhile TBCs Began finding use in Low Risk Aero Applications especially at P&W



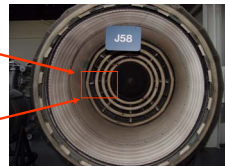
Lockheed SR 71 Blackbird



Pratt & Whitney J58



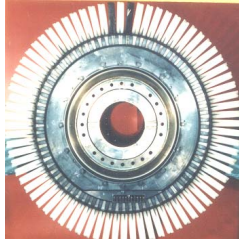
Ceramic Coated Liner and Flame Holders  
Implementation of MSZ TBC Allowed Continuous Use of Afterburner  
and First Sustained Flight Above Mach III of an Air Breathing Engine



After Burner Section

By about 1970, Plasma Sprayed TBC were in use in Commercial Combustors  
Goward, G.W. 1987. Seventeen years of thermal barrier coatings. Paper presented at the 1987 Proceedings of the Workshop on Coatings for Advanced Heat Engines, Castine, Maine, July 27-30. Washington D.C.: U.S. Department of Energy

**Mid 70s, Development of “Modern” Thermal Spray Coatings**  
TBC of zirconia-12%yttria on NiCrAlY survived J-75 engine test



Jack Brown



**Key Accomplishments**

- Use of Yttria as Zirconia Stabilizer
- Use of MCrAlY Type Bond Coat
- First demonstration that Blade TBCs were feasible
- Demonstrated that graded region was not required

Stecura



Liebert



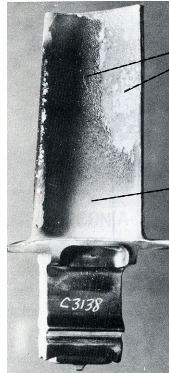
S. Stecura, "Two-Layer Thermal Barrier Coating for Turbine Airfoils— Furnace and Burner Rig Test Results," NASA TM X-3425, National Aeronautics and Space Administration, 1976  
C.H. Liebert and F.S. Stepka, Potential Use of Ceramic Coating as a Thermal Insulation on Cooled Turbine Hardware, NASA TM X-3352, 1976

**Comment from G.W. Goward**  
**-- then of Turbine Components Corp.,**  
**formerly of Pratt & Whitney**

*“Although the engine was run at relatively low pressures, the gas turbine engine community was sufficiently impressed to prompt an explosive increase in development funds and programs to attempt to achieve practical utilization of the coatings on turbine airfoils”*

Goward, G.W. 1987. Seventeen years of thermal barrier coatings. Paper presented at the 1987 Proceedings of the Workshop on Coatings for Advanced Heat Engines, Castine, Maine, July 27-30. Washington D.C.: U.S. Department of Energy.

**The NASA TBC was Tested with Mixed Results in a More Advanced JT9D at P&W, 1977**



SPALLING  
IN HIGH  
TEMPERATURE  
REGIONS

EARLY TBC  
IN TACT IN  
LOWER  
TEMPERATURE  
REGIONS

**Sevcik and Stoner/P&W, 1977:**

Failure correlated better with regions of high temperature than regions of highest compressive stress.

This suggested that mechanisms associated with high temperature must be occurring

***Tom Strangman was involved in the above discussion***

W.R. Sevcik and B.L. Stoner, NASA Contractor Report CR-135360, 1978 (Pratt & Whitney Aircraft)

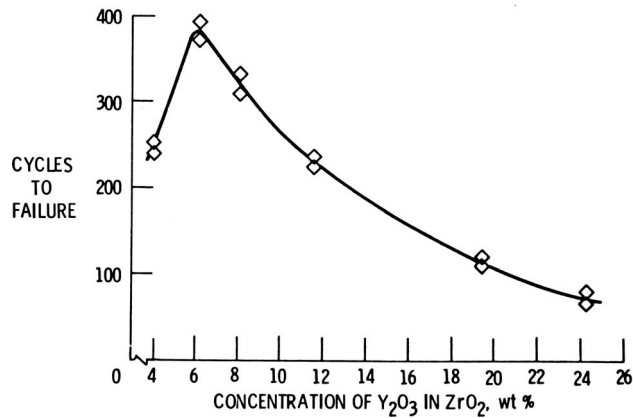
**Comment from Goward, 1987:**

*"The results (of the JT9D test of the NASA TBC) indicated that while the coatings had considerable promise, further development would be required"*

Goward, G.W. 1987. Seventeen years of thermal barrier coatings. Paper presented at the 1987 Proceedings of the Workshop on Coatings for Advanced Heat Engines, Castine, Maine, July 27-30. Washington D.C.: U.S. Department of Energy

## Stecura Reported Optimum Zirconia-Yttria TBC Composition in 1978 – Still the State-of-the-Art!

- Stecura conducted furnace, natural gas torch, and burner rig tests



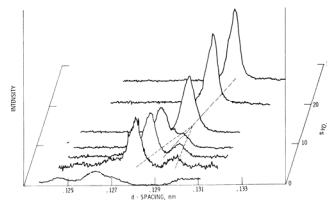
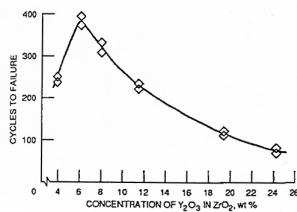
S. Stecura, "Effects of Compositional Changes on the Performance of a Thermal Barrier Coating System," NASA TM-78976, National Aeronautics and Space Administration, 1978

## Compositions Having Optimum Life Were Correlated With Phase Distribution

(Miller, Smialek, Garlick 1981,1983)

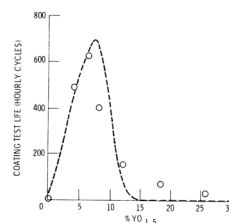
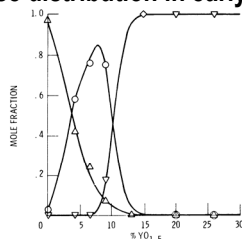
Stecura optimum from 1978

Xray evidence of tetragonal phase



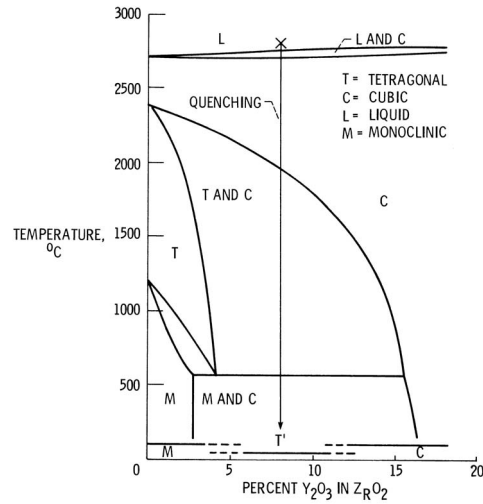
Phase distribution in early TBC

Tetragonal Correlated with Life



R.A. Miller, R.G. Garlick, and J.L. Smialek, Ceram. Soc. Bull., Vol. 62, 1983, pp. 1355-1358

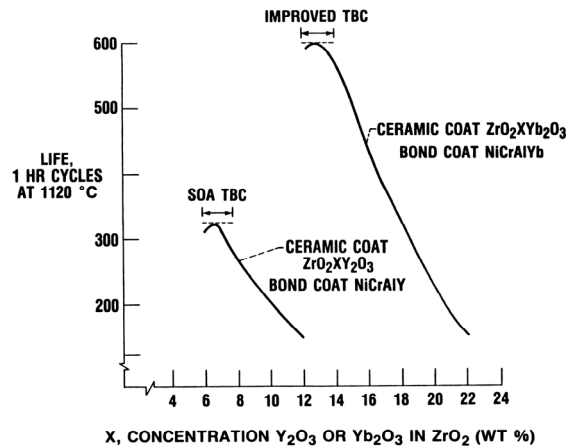
**Optimum Phase was t'-ZrO<sub>2</sub> Phase First Reported by Scott  
(Miller, Smialek, Garlick 1981, 1983)**



H.G. Scott, J. Mater. Sci., 10, 1527-1535 (1975)

**Stecura's Later Work Reported 2X Life for Ytterbia-Stabilized Zirconia on a Yb-Containing Bond Coat**

**IMPROVED TBC SYSTEM YIELDS  $\approx 2X$  LIFE IN LAB TESTS COMPARED TO CURRENT SOA TBC'S**



S. Stecura, New ZrO<sub>2</sub>-Yb<sub>2</sub>O<sub>3</sub> Plasma-Sprayed Coatings for Thermal Barrier Applications, Thin Solid Films, Vol. 150, 1987, pp. 15-40

**In addition to favoring 6-8YSZ, Stecura also  
Recommended Bond Coats with Lower CTE's**

- His eventual favorite MCrAlY was  
Ni – 35Cr – 6Al – Yb (or Y)

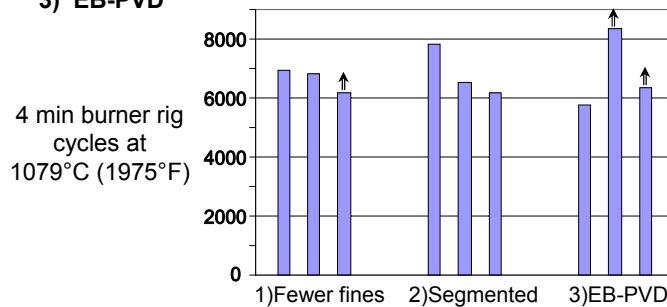
This is a more ductile bond coat due to low aluminum  
and it has lower expansion due to an  $\alpha$ -Cr

S. Stecura, Advanced Thermal Barrier System Bond Coatings for Use on Ni-, Co-, and Fe-Base Alloy Substrates,  
NASA TM 87062, July 1985

**NASA-Sponsored Pratt & Whitney Development Effort  
Identified Three Optimum 6YSZ TBC Microstructures**

**Task II Optimums:**

- 1) Conventionally plasma sprayed with fewer fines (55% -325 mesh)\*
- 2) Segmented plasma sprayed structure from 1" stand-off distance
- 3) EB-PVD



Segmented TBC had thermal conductivity 1.9X conventional optimum  
\*Note that NASA at that time typically used 15% -325mesh)

N.P. Anderson and K.D. Sheffler, Development of Strain Tolerant Thermal Barrier Coating Systems, Tasks I-III, NASA-CR-168251,  
PWA-5777-29, September 1983.

**Arguments Persisted in early 80s over Role of Heat Flux vs. Thermal Expansion Mismatch and Environmental Effects -- even for Burner Rig Testing**

- In the early 1980s some believed that failure occurred due to stresses encountered on heating
  - Those believing heat flux effects caused failure calculated max stress at 2 seconds into heating in burner rig.
- We conducted a series of short- and longer-cycle burner rig experiments and concluded the following:
  - Cracks link up at the interface prior to visible surface cracking or spalling, due primarily to thermal expansion mismatch between ceramic/metal
  - A few cycles after the cracks link up to form a delaminated region (visible as a hot-spot on heating), the rapidly heated unattached portion of the coating spalls on heating
  - Failure is influenced by bond coat plasticity and oxidation at the irregular bond coat/ceramic interface
  - Also, coating life was time and cycle dependent

R. A. Miller and C. E. Lowell, Thin Solid Films 95, 265 (1982)

**Paul Siemers of GE CR&D was another researcher to recognize the importance of bond coat oxidation and plasticity**

***“The durability of thermal barrier coatings is limited by degradation of adhesion by environmental interactions rather than by mechanical stress per se.”***

P.A. Siemens and W.B. Hillig, “Thermal-Barrier-Coated Turbine Blade Study,” NASA CR-165351, National Aeronautics and Space Administration, 1981

### **Other NASA Efforts in the 1980s**

#### **Abradable seals**

P&W, NASA Bob Bill

- First discussion of TBC creep (Firestone, U Illinois)
- This non-textbook use of the term “creep” was controversial!

Later led to thick diesel TBC program

#### **Dirty fuels**

- In-house and DOE and EPRI funding
- Many parallels with CMAS
  - For example Sodium Sulfate does not react with Zirconia-Yttria
    - Rather, when the dew point is less than the coating temperature and the melting point is also less, then liquid Sodium Sulfate wicks into the pores and micro-cracks of the coating leading to a loss of strain tolerance
  - Other impurities such as Vanadium salts also react

RF Firestone, WR Logan, JW Adams - NASA CR-167868, 1982

RA Miller, Ceramic Thermal Barrier Coatings for Electric Utility Gas Turbine Engines, NASA Tech Memo 87288, Jan 1986

RA Miller Analysis of the response of a thermal barrier coating to sodium and vanadium doped combustion gases

NASA Tech Memo 79205, 1979

### **Other NASA Efforts in the 1980s**

#### **Industry trials**

- via coatings group and Liebert's turbine cooling branch
- many different applications

#### **TBCs were in 2 Major NASA projects**

- Energy Efficient Engine with GE
- Engine Component Improvement with P&W
- Both contracts involved analytical assessment of the value of TBCs

C.H. Liebert and F.S. Stepka, Industry Tests of NASA Ceramic Thermal Barrier Coating" NASA Technical Paper 1425, June 1979

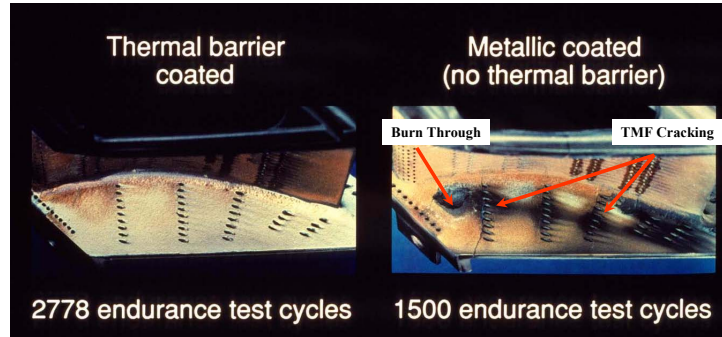
C.H. Liebert and R.A. Miller, Ceramic Thermal Barrier Coatings, I&EC Product Research and Devel., Sept. 1984, 344-349

E.C. Duderstadt and P. Agarwal, "Energy Efficient Engine. High Pressure Turbine Thermal Barrier Coating Support Technology Report," NASA CR-168037, National Aeronautics and Space Administration, 1983



**In 1985 Pratt & Whitney used Zirconia-Yttria TBC  
to Fix a Vane Platform Endurance Issue**

- Application of Thermal Spray TBC Eliminated Distress of Vane Platform
- Extended Service Life to 18,000 hrs



- P&W shared these results with NASA leading to TBC task in  
*Hot Section Technology (HOST) Life Prediction Program*

S. Manning Meier, D.M. Nissley, and K.D. Sheffler, Status of Ceramic Thermal Barrier Thermal Barrier Coatings – Gas Turbine Applications and Life Prediction Method, Proceedings of the 1990 Coatings for Advanced Heat Engines Workshop, Aug. 6-9, Castine ME, II-57-65  
S. Manning Meier and D.K. Gupta, The evolution of thermal barrier coatings in gas turbine engine applications  
Journal of Engineering for Gas Turbines and Power; Vol. 116, 250-257, 1994

This slide and the next 14 that follow are from a 1987 presentation on progress under the Hot Section Technology (HOST) TBC life prediction program. They are repeated here as history

**HOST TBC LIFE PREDICTION**

**NASA**

C. STEARNS  
R. MILLER  
J. NESBITT  
S. LEVINE  
J. MERUTKA

**GE**

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\*Added to acknowledge post 1987 contribution  
R. A. Miller, J. Eng. Gas Turbines Power 109, 448 (1987)

CD-87-29053

## **APPROACH TO TBC LIFE MODEL DEVELOPMENT**

- **INITIAL LABORATORY MODEL (NASA)**
  - UNDERSTAND FAILURE MECHANISMS
  - FORMULATE MECHANISM MATHEMATICALLY
  - COLLECT LABORATORY LIFE DATA
  - FIT MODEL TO LIVES
- **ENGINE CAPABLE MODELS (PWA, GTEC, GE CONTRACTS)**
  - FURTHER UNDERSTANDING
  - FORMULATE MATHEMATICALLY
  - COLLECT LIFE DATA OVER MANY CONDITIONS ON BOM SYSTEM
  - MEASURE MATERIALS PROPERTIES
  - FIT MODEL TO LIVES
  - EXTRAPOLATE TO ENGINE MISSIONS
- **DETAILED FINITE ELEMENT  $\sigma$ - $\epsilon$  ANALYSIS (CSU, NASA)**

CD-87-29050

## **UNDERSTANDING OF FAILURE MECHANISMS SUFFICIENT TO ALLOW MODELING**

### **FAILURE BY CRACKING/DELAMINATION IN CERAMIC NEAR INTERFACE**

- PROGRESSIVE CRACKING OBSERVED
- $\sigma$ ,  $\epsilon$  MODELED

### **EMPIRICAL OBSERVATIONS**

#### **CYCLIC COMPONENT TO FAILURE**

- THERMAL EXPANSION MISMATCH<sup>a</sup>
- HEATING TRANSIENTS

#### **TIME-AT-TEMPERATURE COMPONENT**

- OXIDATION<sup>a</sup>
- PHASE CHANGES
- SINTERING
- DIFFUSION
- CREEP

<sup>a</sup>KEY FACTORS INCLUDED IN PRELIMINARY NASA MODEL

CD-87-29052

## DETAILED FINITE ELEMENT STRESS ANALYSIS YIELDS INSIGHTS INTO TBC BEHAVIOR

700 °C (STRESS FREE)–600 °C

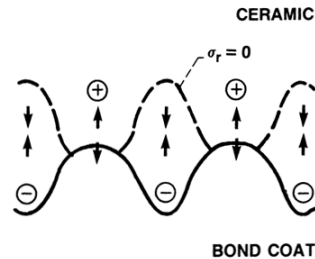
HIGH TENSILE RADIAL STRESS IN CERAMIC NEAR INTERFACE

LOWER  $\sigma_r$  THROUGH LOWER

- $E_{\text{CERAMIC}}$
- $\alpha_{\text{CERAMIC}} - \alpha_{\text{BOND COAT}}$
- YIELD STRENGTH OF CERAMIC
- ROUGHNESS
- OXIDATION

WEAK EFFECT ON  $\sigma_r$  FROM

- $\alpha_{\text{SUBSTRATE}}$
- $\mu_{\text{BOND COAT}}$
- $E_{\text{BOND COAT}}$



CD-87-29044

G. Chang, W. Phucharoen and R. Miller Surf. Coat. Technol. 30 (1987), p. 13.

Similar insights in Evans, A.G., G.B. Crumley, and R.E. Demaray. 1983. On the mechanical behavior of brittle coatings and layers. Oxidation of Metals 20(5/6): 193-216.

## NASA PRELIMINARY TBC LIFE MODEL

- ONE COATING SYSTEM
- TIME-AT-TEMPERATURE EFFECT
  - OXIDATION ONLY,  $W_N$
- CYCLE FREQUENCY EFFECT
  - SLOW CRACK GROWTH (MICROCRACK LINK UP IN CERAMIC)

$$\frac{da}{dN} = A \epsilon_e^b a^c$$

(FATIGUE/MINER'S LAW APPROACH ALSO NOTED)

- ASSUMED RELATIONSHIP BETWEEN WEIGHT GAIN AND STRAIN

$$\epsilon_e = (\epsilon_f - \epsilon_r) (W_N / W_c)^m + \epsilon_r$$

CD-87-29056

R.A. Miller, Oxidation-Based Model for Thermal Barrier Coating Life, J. Am. Ceram. Soc., Vol. 67, 1984, pp. 517–521

## NASA PRELIMINARY TBC LIFE MODEL CONTINUED

### ■ RESULTING MODEL

$$\sum_{N=1}^{N_f} \left[ (1 - \epsilon_r/\epsilon_f) (W_N/W_C)^m + \epsilon_r/\epsilon_f \right]^b$$

### ■ ALTERNATIVE ASSUMPTION OF STRENGTH DEGRADATION FROM $\epsilon_{f0}$ TO $\epsilon_r$

$$\epsilon_f/\epsilon_r = (1 - \epsilon_{f0}/\epsilon_r) (W_N/W_C)^m + \epsilon_{f0}/\epsilon_r$$

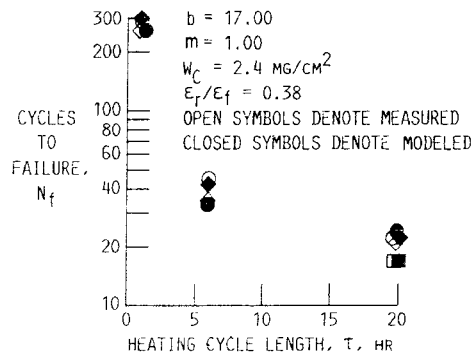
### ■ RESULTING ALTERNATIVE MODEL

$$\sum_{N=1}^{N_f} \left[ (1 - \epsilon_{f0}/\epsilon_r) (W_N/W_C)^m + \epsilon_{f0}/\epsilon_r \right]^{-b} = 1$$

CD-87-29057

## PRELIMINARY MODEL YIELDS GOOD AGREEMENT BETWEEN EXPERIMENTAL AND CALCULATED TBC LIVES

$$\text{MODEL: } \sum_{N=1}^{N_f} \left[ \left( 1 - \frac{\epsilon_r}{\epsilon_f} \right) \left( \frac{W_N}{W_C} \right)^m + \frac{\epsilon_r}{\epsilon_f} \right]^b = 1$$



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## **P&W HOST ACCOMPLISHMENTS**

### **DEGRADATION MODES IDENTIFIED**

- Mechanical (major mode)**
  - Near interfacial ceramic cracking
  - Apparent near-interface ceramic weakening
- Oxidation (major mode)**
  - Oxidation effect phenomenologically characterized
  - Complex oxide scale characterized
  - Interaction mechanism not understood
- Hot corrosion (minor mode)**
  - Not observed in flight service
  - Threshold corrodant level identified in lab
- Erosion (minor mode)**
  - Isolated occurrence in flight service
  - Limited lab characterization needed
- F/BMOD (minor model)**
  - Not identified in flight service
  - Experimental engines exhibit high –resistance

## **P&W HOST ACCOMPLISHMENTS**

### **MAJOR MODE CORRELATIVE LIFE**

#### **MODEL PROPOSED**

- Fatigue based model**
- Reversed ceramic plastic strain is primary driving force**
- Oxidation acts to "weaken" ceramic**
- Preliminary correlation coefficient 0.89**  
(90 experimental data points)
- Upgraded analysis in progress**
- Incorporates improved ceramic behavior model**
- Oxidation contribution improved by use of NASA data**

Thermal Barrier Coating Life Prediction Model Development: Phase I-Final Report, NASA CR 182230  
J.T. DeMasi, K.D. Sheffler, M. Ortiz - National Aeronautics and Space Administration, Washington DC, 1989  
Thermal barrier coating life prediction model development—phase II  
S.M. Meier, D.M. Nissley, K.D. Sheffler - NASA CR-18911, July, 1991

### PWA/SwRI TBC LIFE MODEL

- BILL-OF-MATERIAL COATING SYSTEM
- TIME-AT-TEMPERATURE EFFECT
  - OXIDATION ONLY,  $\delta$
  - ARRHENIUS LAW
- CYCLE FREQUENCY EFFECT
  - INELASTIC FATIGUE MODEL

$$N_f = (\Delta\epsilon_i / \Delta\epsilon_f)^b$$

$$\Delta\epsilon_i = \Delta\alpha \Delta T + \Delta\epsilon_h + \Delta\epsilon_c - 2 \frac{\sigma_{ys}}{E}$$

ASSUMED STRENGTH DEGRADATION DUE TO OXIDATION

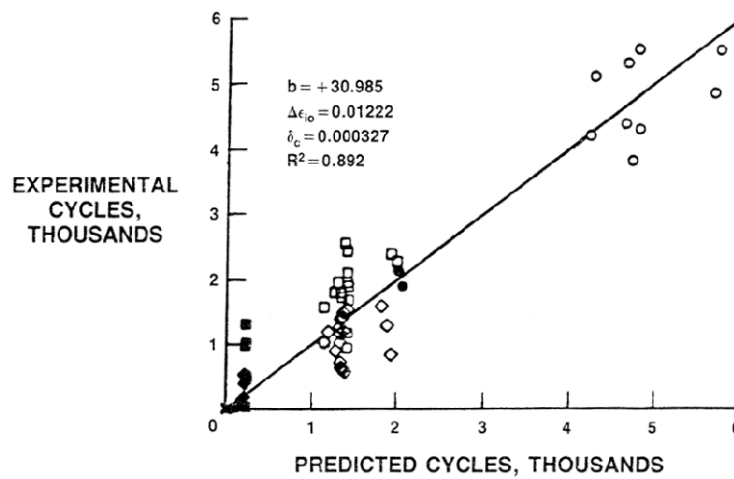
$$\Delta\epsilon_f = \Delta\epsilon_{f0} (1 - \delta/\delta_c)^c + \Delta\epsilon_i (\delta/\delta_c)^d$$

- MINERS RULE

$$\sum_{N=1}^{N_i} \frac{1}{N} \geq 1$$

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### CORRELATION BETWEEN MEASURED AND MODELED LIVES (PRELIMINARY PRATT & WHITNEY DATA)



CD-87-24362

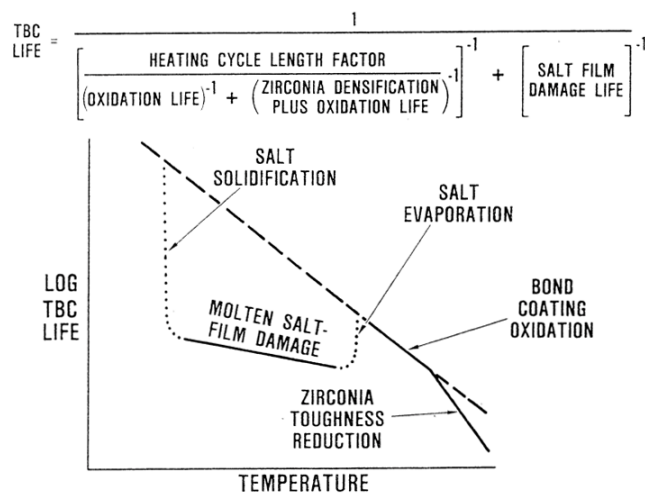
## GARRETT TBC LIFE MODELING APPROACH

|                              |   |   |
|------------------------------|---|---|
| TBC<br>DEGRADATION =<br>RATE | <u>F<sub>1</sub> (MECHANICAL)</u>   | <u>+ F<sub>2</sub> (OXIDATION)</u>  |
|                              | <ul style="list-style-type: none"> <li>• COATING STRESSES</li> <li>• TEMPERATURE</li> <li>• MATERIAL SYSTEM                             <ul style="list-style-type: none"> <li>- K<sub>IC</sub></li> <li>- FLAW SIZE</li> <li>- ELASTIC MODULUS</li> <li>- SPALLING STRAIN</li> </ul> </li> </ul> | <ul style="list-style-type: none"> <li>• TEMPERATURE</li> <li>• TIME</li> <li>• MATERIALS SYSTEM</li> </ul> |
|                              | <u>+ F<sub>3</sub> (SALT DEPOSITION)</u>  |   |
|                              | <ul style="list-style-type: none"> <li>• ALTITUDE (SALT INGESTION)</li> <li>• TURBINE PRESSURE</li> <li>• SALT EVAPORATION</li> <li>• SALT SOLIDIFICATION</li> <li>• TEMPERATURE</li> <li>• GAS VELOCITY</li> <li>• AIRCRAFT LOCATION</li> <li>• MATERIALS SYSTEM</li> </ul>                      |   |

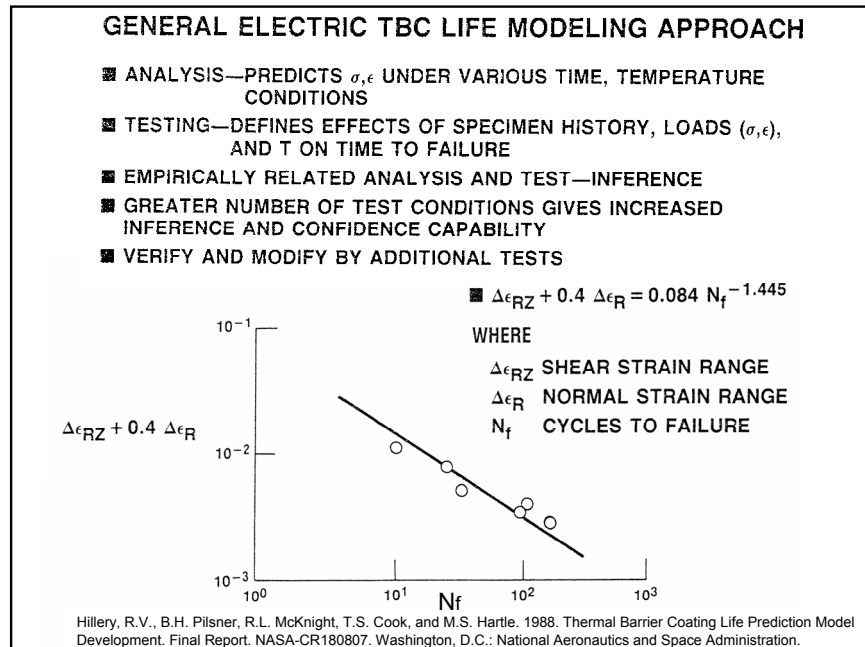
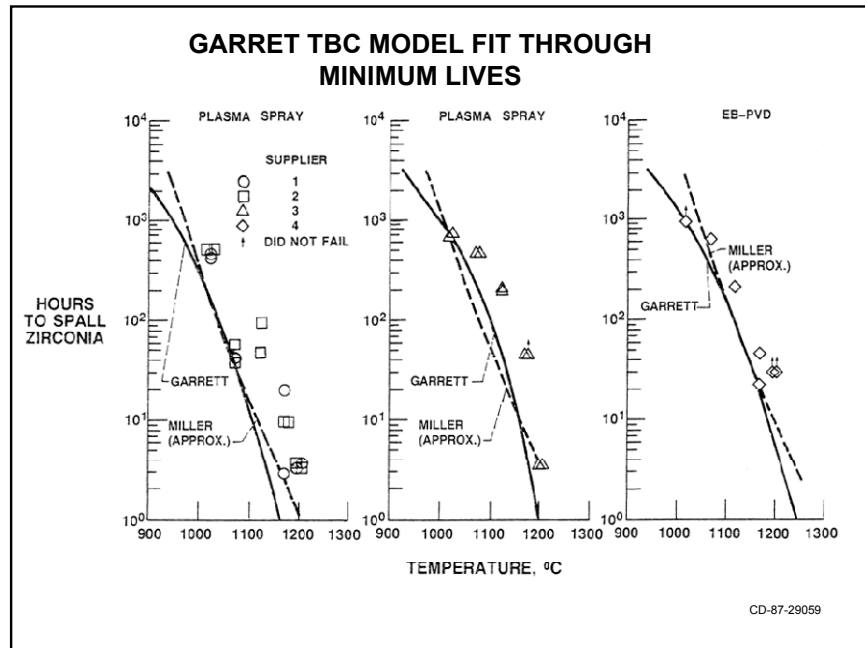
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T.E. Strangman, J. Neumann, and A. Liu, "Thermal Barrier Coating Life-Prediction Model Development," NASA CR-179648, National Aeronautics and Space Administration, 1987

## GARRETT TBC LIFE MODEL HAS THREE DEGRADATION MODES

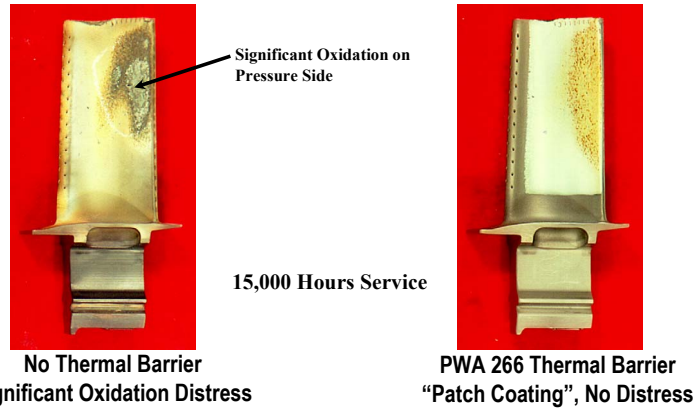


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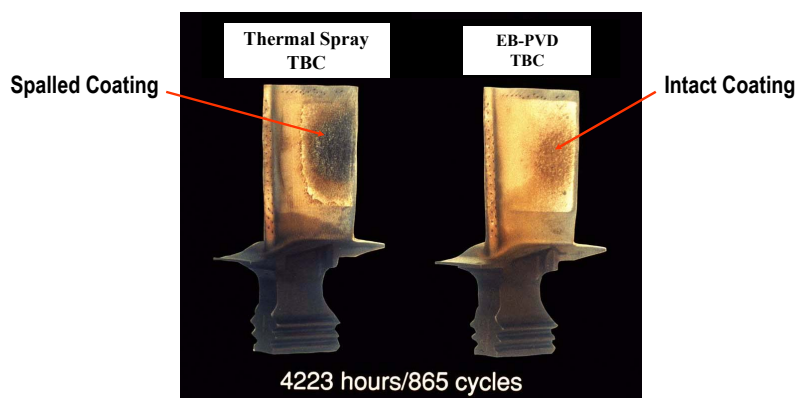
**By 1989 an Infant Mortality Issue had been Overcome and  
EB-PVD TBCs Were Introduced onto Turbine  
Blades in Engines in Revenue Service**



- First Introduced on South African Airways B747
- High Altitude Airport, High Mean Ambient Temperature Resulted in  
**Unexpected Airfoil Distress**

Referenced in M. Peters, C. Leyens, U. Schulz, W. A. Kaysser EB-PVD Thermal Barrier Coatings for Aeroengines and Gas Turbines, Advanced Engineering Materials, 3, 193-204, 2001

**EB-PVD TBCs Remain the Coating of Choice for 1<sup>st</sup> Blade**



This and previous slide and slides 6,7, and 10 based on slides from M. Malony N. Ulion and R.A. Miller, Irsee 2003 Presentation

## **Concluding Remarks --**

### **NASA had Substantial Involvement in Early TBC Research and TBC Research Continued through the 90s and 00s ...**

#### **1990s:**

##### **Thick Diesel**

- With the Army Research Lab at NASA and Caterpillar
- Built on thick shroud work
- Dongming Zhu joined NASA team

##### **EBCs**

- Built on initial Solar Turbines Research

##### **High Speed Research**

- NASA/GE/P&W
- Began a period of strong interaction with industry
- A useful reality check!

#### **2000s:**

##### **Ultra Efficient Engine Technology**

- Low k TBC / High heat flux laser rig testing
- EBCs

D. Zhu and R.A. Miller, Investigation of Thermal High Cycle and Low Cycle Fatigue Mechanisms of Thick Thermal Barrier Coatings, Materials Science and Engineer. Vol. A245, pp. 212-223, 1998  
K.N. Lee, R.A. Miller, and N.S. Jacobson, New generation of plasma-sprayed mullite coatings on silicon-carbide. J. Am. Ceram. Soc. 78 3 (1995), pp. 705-710  
D. Zhu and R.A. Miller, Development of Advanced Low Conductivity Thermal Barrier Coatings, Int. J. Appl. Ceram. Technol., Vol. 1, 86-94, 2004

## **Concluding Remarks --**

### **... and TBC Research Continues Today**

#### **Fundamental Aeronautics Program**

- Erosion
  - Rotorcraft oriented; first blade EB-PVD
  - Burner rig has been modified for particle injection
- Damping
  - High force/high frequency/high temperature capability
- TBC Lfing
  - Small program aimed at Supersonic mission
- EBCs
  - Current task is also aimed at Supersonics

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